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SOME PROBLEMS OF STELLAR MOTIONS*

By R. M. PETRIE

THE study of the motions of the stars has long been an important branch of astronomy. It may be said to date from 1718 when Halley presented evidence to the Royal Society demonstrating the change in apparent position of the three bright stars *Aldebaran*, *Sirius*, *Betelgeuze*, and *Arcturus*. The problems considered in the subject of stellar motions have a wide range; on the one hand detailed investigation of the mechanics of an isolated double-star system, at the other extreme the grand conception of the dynamics and organization of a universe. The student must consider matters as diverse as the orbital motion of the earth about the sun and the processes by which atoms absorb and emit radiation in stellar atmospheres.

The appeal of our subject has attracted many great minds of the past and the attraction is as strong as ever. Today the challenge of the dynamical problems posed by the movements of the stars in relation to the stellar system calls forth extensive and profound researches both observational and theoretical. We cannot, obviously, cover the subject in the space of a single lecture and must content ourselves with an examination of a few selected

*A lecture delivered before the Victoria and Vancouver Centres of the Society.

topics. Such a procedure lacks continuity and homogeneity but has its compensations by affording us glimpses of the more exciting and spectacular aspects of our study.

I shall assume that you are acquainted in a general way with the measurement of the speeds of the stars and, beyond a few definitions, shall not describe the techniques of the practical problem. The motion of a star through space cannot be measured directly but is manifested in two ways, first a drifting motion across the sky (after local effects such as diurnal motion, precession, etc., are allowed for) recognized as a gradual change in the position of the star and called *proper motion;* and secondly the approach or recession of the star relative to the earth (or sun) and called *radial velocity.* The radial velocity can be measured directly in miles per second but the proper motion is a change in position or direction and is measured in change of angle. The amount, in miles per second, can be calculated only when we know the distance to the star. When this calculation is performed the motion "across" the sky is known in miles per second and we refer to it as the *cross motion* or *tangential velocity.*

The relation between the observable parts of a star's motion and its true space motion is shown in figure 1 where S is the space motion and T and R are the tangential and radial velocities. The angular change or proper motion is given by the angle M.

The proper motion is determined by measuring the positions of a star at two times separated by twenty years or more. This is now ordinarily done by photography and the change in position is measured directly by comparing the two photographs. Proper motions are expressed in seconds of arc per year (the diameter of the moon is approximately 1900 seconds). The largest annual motion is some 10″.2 and then in order are 8″.7 and 7″.0; about two hundred stars are known to have annual motions greater than one second but the average values are much less. For several thousand solar-type stars the average proper motion is 0″.16 per year.

As an example of this phase of our subject consider the nearby and bright star *Arcturus* which has a large annual proper motion of 2″.29. Its distance is known with considerable certainty to be 350 light-years and so we find its tangential or cross speed to be

90 miles per second. The direction of the motion, also found from the photographs, is about 30° west of south.

Astronomy today is indebted to workers of former generations whose devoted and self-sacrificing labours supplied the basic observations. Their efforts reached fruition a few years ago in the publication of an invaluable *General Catalogue* containing the positions and proper motions of some 33,000 stars.

The radial speeds (line-of-sight speeds) are determined by photographing the spectrum of a star and comparing the wave-lengths of the identified radiations with those of a terrestrial standard. According to the principle discovered by Doppler in 1842 and formalized by Fizeau in 1848 the wave-length change gives us the line-of-sight motion directly in miles per second. The stellar spectrograph, a highly specialized instrument, has now been so

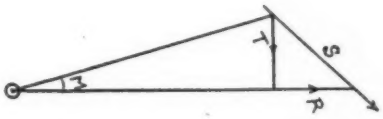

FIG. 1.—The space motion of the star is shown by the arrow *S*. The observed motions are the angle *M*, which is the proper motion, and the arrow *R*, which is the radial velocity. The arrow *T*, is the tangential velocity which can be calculated when the proper motion and distance are known.

developed that line-of-sight speeds can be measured with high accuracy. Good mechanical and optical design are required in the spectrograph and meticulous care is necessary in measuring the photographed spectral features. The spectrum is examined under a microscope and micrometer settings are made to a fifty-thousandth part of an inch.

Radial speeds have been measured for some 10,000 stars, practically all of these since 1900. In combination with the tangential speeds we may calculate the amount and direction of the motions of many stars. Returning to our example of *Arcturus* we find the radial velocity to be -3.5 miles per second, the negative sign indicating approach. Referring to figure 1 we see that the space motion may now be found since $S^2 = R^2 + T^2$ and for *Arcturus* this becomes approximately 91 miles per second.

With this introduction we may now survey some of the applications of stellar motions to astronomical problems.

The Solar Parallax

A fundamental quantity in astronomy is the distance from the earth to the sun, usually referred to as the solar parallax. It is the fundamental yardstick of the universe; upon it depends all our knowledge of the distances, luminosities, and dimensions of stars, the size of our galaxy and the greater universe of spiral nebulae. The importance of this unit is so great that astronomy has spared no effort to obtain the most accurate value possible. In the past

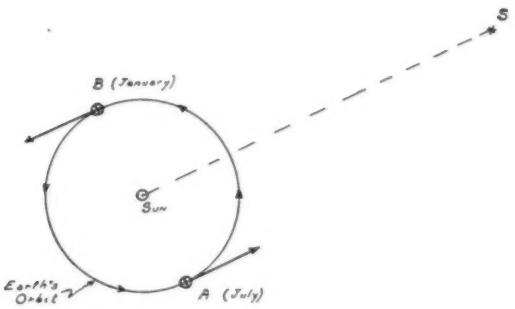

Fig. 2.—The circle represents the earth's orbit about the sun. In July (*A*) we are approaching the star, at *S*, while in January (*B*) we are receding from it. Spectroscopic observations of the star at these times will give the orbital speed of the earth.

the problem has been attacked by laborious geometrical methods such as observations of transits of *Venus* and *Mercury* and of close approaches of minor planets notably *Eros*. Although the sun is our nearest stellar neighbour it is too far away for an accurate triangulation on the surface of the earth such as suffices to determine the moon's distance and so we must employ the indirect methods referred to above.

In 1892 it was pointed out by Campbell, the great pioneer of radial-velocity work, that the spectroscope held the promise of an accurate and much less laborious solution. The method is beautiful

in its simplicity and is a fine example of a valuable by-product of stellar motion studies. The principle is illustrated in figure 2, where the motion of the earth about the sun is shown and also the position of a star at *S*. Notice that the earth at the point *A* is approaching the star because of orbital motion and at *B*, six months later, is receding from the star. Now, if the star has a constant speed with respect to the sun our two observations will give us both the speed of the star and the earth's speed in its orbit. The earth's orbital motion is related to the distance sun-to-earth by well established orbit theory and known constants and so, having determined the orbital motion, we find the distance. The desired accuracy is obtained by making a sufficient number of observations of suitably-located bright stars with a powerful spectrograph. The following tabulation lists some values of the solar parallax determined from radial-velocity data and, for comparison, the most recent value derived by the geometrical method from observations of *Eros* at its close approach of 1931. It should be remarked that the Victoria result, in Table I is obtained from

TABLE I—THE EARTH'S DISTANCE FROM THE SUN

Observatory	Stars	Number of Plates	Solar Parallax	Distance Earth to Sun
Cape	19 Stars		8″.802	92,900,000 miles
Mount Wilson	α *Bootis*	37	8.805	92,800,000 "
Victoria	7 Stars	70	8.772	93,200,000 "
1931 Co-operative	*Eros*	1800	8.790	93,000,000 "

moderate dispersion spectrograms drawn from the Observatory's collection and not specifically arranged to give the most favourable determination of the solar parallax. The close agreement with the values derived from better material is a tribute to the power of the spectroscopic method.

Consider now the enormous saving of effort afforded by the spectroscopic method. For the 1931 opposition of *Eros* a co-operative plan was arranged whereby thirty telescopes at twenty-four observatories were devoted for some months to the photography of *Eros* and field stars. Approximately 1800 photographs

were measured in some detail, followed by the task of reduction and analysis of the measures. The final result appears fifteen years after the opposition. In contrast let us see what is involved in the spectroscopic method. A score or so hours of observing time with one telescope equipped with a spectrograph together with one or two man-months yields a result rivalling in precision, and exceeding in simplicity, that given by the geometrical method.

The relative efficiency of the dynamical method is so overwhelming that astronomers may now well consider that the laborious and expensive geometrical method may be dispensed with.

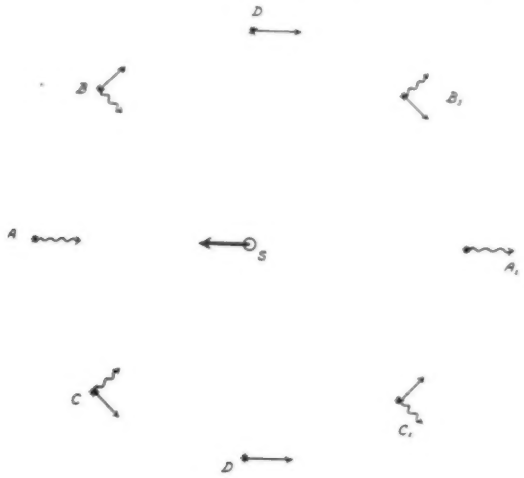

FIG. 3.—The effect of the motion of the sun upon stars at various locations on the sky. The heavy arrow at *S* is the sun's motion. The straight lines at *B*, *C*, *D*, etc., are the cross motions of the stars observed as proper motions while the wavy lines show the amount and direction of the observed speeds of approach and recession.

THE SOLAR MOTION

One of the major problems in stellar studies during the first quarter of this century was the determination of the solar motion. This is the speed of the sun in amount and direction with respect to a large number of stars. The solar motion is of interest in itself

and is important in the statistical study of the distances and distribution of stars in the stellar system. Furthermore we may, by allowing for the sun's speed, free the observed stellar motions of its influence and so place our studies upon a more fundamental and less anthropocentric basis.

The sun's way among the stars may be found from the observed stellar motions. The principle of the method may be understood from figure 3 where the sun at S is moving in the direction indicated by the arrow. Assuming that on the average the peculiar motions of a number of stars located close together on the sky will cancel one another, we see that the stars at A will appear to be approaching us and those at A_1 will appear to be receding. At B and C the proper motions will be away from the point A and the radial velocities will indicate approach. At B_1 and C_1 the radial speeds will show recession while the proper motions will be directed toward A_1. At the point D, the line-of-sight motions will be zero and the proper motions will be at a maximum directed oppositely to the sun's motion.

Considerations of the sort outlined above led the great astronomer, Sir William Herschel, in 1783, to the first determination of the solar motion from the proper motions of only thirteen stars. He found that the sun was moving toward a point near the star *lambda Herculis* not far from the place indicated by modern determinations based upon hundreds of stars. This masterly achievement is an example of the genius which Herschel brought to bear upon so many problems of astronomy.

Notice that the proper motions give us the *direction* in which the sun is going but cannot tell us the speed unless we employ the always uncertain stellar distances. But here the radial velocities come to our aid and will tell us (see figure 3) the speed and direction of the sun's flight through space relative to the stars in our part of the stellar system.

The observed radial velocities exhibit very well the effect of the solar motion. From the *General Catalogue of Radial Velocities* compiled by Dr. J. H. Moore at the Lick Observatory, I find average velocities for regions of the sky 20° on a side as given in Table II. Even with the small samples used it is plain from

TABLE II—AVERAGE RADIAL VELOCITIES AT FOUR POINTS

Position	Stars Approaching	Stars Receding	Number Stars	Average Velocity
	Per cent	Per cent		
0^h, 0°; *Pisces*	47	53	49	− 2 mi./sec.
6^h, − 30°; *Canis Major*	24	76	49	+ 21
12^h, 0°; *Leo*	51	49	51	0
18^h, + 30°; *Hercules*	88	12	89	− 14

Table II that the sun is moving away from the *Canis Major-Puppis* region and toward the region of *Hercules*, where 88 per cent. of the stars in the sample are approaching us. Note also that the midway regions, at the equinoxes, have practically equal numbers of stars approaching and receding.

Many determinations of the solar motion have been made with the result that the properties of this motion are well established. Table III contains a few sample solutions taken from the several dozen available in the literature and shows that the sun, with respect to the stars considered, is flying through space at the enormous speed of nearly 50,000 miles per hour.

TABLE III—THE SOLAR MOTION

Reference Objects	No.	Solar Apex R.A. Decl.	Solar Speed	*K*-term	Material
O - B5	378	276°, + 30°			proper motions
A	484	263°, + 23°			proper motions
K	728	273°, + 37°			proper motions
O - B5	464	284°, + 27°	13 mi./sec.	+ 3.1 mi./sec.	radial velocities
A	697	264°, + 22°	11	+ 0.3	radial velocities
K	984	274°, + 28°	14	+ 0.6	radial velocities
Globular Clusters		300°, + 35°	200		radial velocities

Several interesting facts are revealed in Table III. While all determinations agree in a general way there are some real discrepancies in the derived position of the solar apex. For example

the A stars give a solar motion farther west and to the south of that found from the other spectral types while the speed is also less. Such differences cast doubt upon our assumption that stellar movements are entirely at random and demand the consideration of systematic trends in motions and distribution.

An unsolved problem arises from the presence of an additional motion found for the highly luminous and hot O and B stars, and referred to as the *K*-term in column six of Table III. Interpreted literally it means that the O and B stars are flying away from the sun in all directions with an average rate of recession of 3 miles per second. The *K*-term is negligible for other spectral types. Some recent evidence for very distant B stars suggests that their average motion is the reverse, i.e., approach. This curious phenomenon has puzzled astronomers for four decades and no satisfactory explanation has been developed as yet. The matter is not only one of stellar movements but is complicated by the manner in which stellar atmospheric conditions affect the radiations absorbed and emitted by the atoms. The mystery of the *K*-term is one of the outstanding problems of present-day radial-velocity work.

The most remarkable result in Table III comes from the values given by the globular clusters. They furnish a solar apex agreeing roughly, when one considers the observational difficulties, with that derived from the nearer stars but the speed of the sun is found to be fully *two hundred* miles per second instead of a mere twelve or thirteen. This value is confirmed by observations of the extra-galactic nebulae. Thus our sun is jogging along sedately at twelve miles per second with respect to our neighbouring suns but is dashing headlong through space at some two hundred miles per second when we measure the motion by remote objects less intimately connected with the stellar system. We shall have occasion to return to this important result.

General Problems

We turn now to more general aspects of the subject and find a vast and attractive field for study, research, and speculation, leading ultimately to an appreciation of the structure, dimensions, and dynamics of our galactic system. Two important general features must now be described.

(*a*) *Star Streaming.* Early analysis of stellar movements were based on the idea that the motions were distributed at random both as to direction and speed. The stars were pictured as moving quite haphazardly, just as we think of the molecules of gas in this room to be moving without favouring any direction. This conception had to be abandoned in 1905 when the studies of the great Dutch astronomer, Kapteyn, showed that certain directions of motion are preferred by the stars. The phenomenon is called star streaming and is found to be followed by stars as far as 5000 light-years removed from the sun. The preferential motion is along a line which points to the constellation *Orion* and the antipodal point in the constellation *Scutum*. These points are called the vertices of star streaming; they lie in the plane of the Milky Way and the line points toward, but not directly at, the centre of our system. Numerical analysis shows that the average speed parallel to this line (after the solar motion is eliminated) is about fifty per cent. greater than that perpendicular to it.

(*b*) *The Asymmetry of Motions.* A remarkable distribution of the direction of motion of the high-velocity stars was discovered from proper motion studies in 1918 and, independently, from radial-velocity data the following year. By high-velocity stars are meant those having space motions, relative to the sun, in excess of 50 miles per second. When the directions of the space motions are calculated from the radial and proper motion components it is found that, contrary to expectation, the high speeds are directed toward one hemisphere and do not exhibit a uniform or random distribution. Or, to put it in another way, the high speed stars avoid moving in the direction of the hemisphere centred approximately in the constellation *Cygnus*. This curious behaviour is shared by all fast moving stars and is also shown by the globular clusters. It is obviously of fundamental significance and requires explanation in any rational description of the stellar system.

The Galactic Rotation

The shape of our stellar system, a greatly flattened ellipsoid, and its isolated position in space, some three-quarters of a million light-years from the nearest complete spiral nebula, suggested to astronomers more than a century ago that our Milky Way system

or galaxy might be in rotation. The peculiarities described in the above section, star-streaming and the asymmetric drift, encouraged and even demanded some dynamical explanation. Theoretical studies, as pointed out by Eddington, suggested that the mere existence of our galactic system of the present shape and constitution required that the stars be moving in some kind of orbital form.

The speculations were given more definite form by Lindblad in 1925 and Oort in 1928. The latter visualized the galaxy as a kind of "super" solar-system in which the stars are moving in more or less circular orbits about the central mass. He was able to show that certain consequences of this galactic rotation should be observable in the proper motions and radial velocities after being freed from the effect of solar motion.

Picture for a moment the solar system with planets circling within and without the earth's orbit. The inner planets, because of their greater speed, will approach the earth, overtake it, and pass it while we in turn will catch up to, and pass by, the outer planets. So it is in the galaxy. Stars between us and the centre will whirl past us, and recede into the void; stars outside our orbit will be overtaken and then left behind as we circle the distant centre. Applying these ideas to stellar motions we expect to find periodic motions of approach and recession and also periodic effects in the proper motions as we examine stars in all galactic longitudes, that is, all the way along the circle of the Milky Way.

Oort was able to support his ideas with existing observational material which was barely adequate for his purpose, but abundant verification was soon supplied (1930) by Plaskett and Pearce at Victoria who had just then completed an extensive programme of radial velocities of the distant O and B stars. Their radial-velocity observations showed that the rotating galaxy was, in main outline, correctly described by Oort's theory and they were able to give the direction to the centre of the galaxy and the differential effect upon radial velocities caused by the rotation. The Victoria results showed that the radial-velocity effect amounted to some 3 miles per second for every thousand light-years from the sun. It is apparent, therefore, that only stars at great distances yield positive results regarding the galactic rotation. Plaskett and Pearce

showed from dynamical results that the sun was describing a vast orbit about a remote centre located in the direction of, and far beyond, the great star clouds in the constellation *Sagittarius*. This was confirmation of earlier results based upon star counts and the distribution of the globular clusters.

The above results were followed by other analyses of stellar motions which arrived at substantially the same conclusions placing the rotating galaxy upon the status of an established phenomenon. A good example of the radial-velocity effect is given in Table IV, extracted from observations of very distant *Cepheid* variables made

TABLE IV—GALACTIC ROTATION EFFECT ON RADIAL VELOCITIES

Distance of Star Group	Residual Radial Velocity Due to Galactic Rotation
1370 light-years	+ 7 mi./sec.
3450 light-years	+ 15
5400 light-years	+ 25
7500 light-years	+ 24

at the Mount Wilson Observatory by Joy. His most distant group was farther away than stars used by Plaskett and Pearce and shows the large residual velocity of 24 miles per second corresponding to a rotational differential speed of approximately 3 miles per second for every thousand light-years.

The effects described in the preceding section may now be explained. The huge solar motion of 200 miles per second relative to the globular clusters is seen to be the total motion of the sun about the centre since the clusters do not partake of the rotational motion being distributed more or less symmetrically at great distances from the centre. The motion of the sun is in the direction of *Cygnus* and this is about 90 degrees from the direction to the galactic centre.

The avoidance of this direction by the high velocity stars is a consequence of the galactic rotation. Since the sun travels toward *Cygnus* at 200 miles per second the total velocity of a star moving in that direction would be 200 + 50 or 250 miles per second (for a

relative stellar velocity of 50 mi./sec.) and this is too much for the gravitational field of the galaxy to control. The star would then escape from the system and so we do not observe velocities of this kind. On the other hand, the observed high velocity stars are seen to be in reality slow moving objects which are left behind at a rapid rate by the speeding sun and therefore appear to move toward the hemisphere antipodal to the constellation *Cygnus*.

Star streaming is partially explained by the existence of a number of elongated elliptical orbits similar to those pursued by most comets in the solar system. The result of such orbits would be to give a directional effect in stellar motions pointing toward the galactic centre which is what we observe. It should be noted however that this explanation, if proved to be correct, means that the galaxy is not in a steady state or permanent condition, but that its natural state is one of turbulence and change.

As a result of the velocity studies and Oort's model as a working hypothesis it is possible to calculate the principal dynamical features of our galaxy as follows:

Diameter of Galaxy	=	58,000 light-years
Distance from sun to centre	=	19,000 light-years
Speed of sun	=	200 mi./sec.
Period of solar revolution	=	220,000,000 years
Mass of Galaxy	=	200,000,000,000 solar units
Number of Stars	=	100,000,000,000

Thus the study of stellar motions has taken us far into space and given a glimpse of the nature and organization of our universe.

Conclusion

Limitations of time have restricted this discussion to a few topics and have made necessary the omission of several important chapters of stellar motions. The fascinating story of Moving Star Clusters has not been told. Another omission is that great branch of astronomy devoted to the study of double and multiple stars. In this field dynamical studies have revealed in a marvellous way the nature of binary stars and mathematical developments have obtained great power and precision. The matters discussed above have dealt with motions subject to the general galactic field but there is an important and growing accumulation of knowledge

regarding motions perpendicular to the galactic plane. The study of these motions will yield information about the structure of the galaxy in the neighbourhood of the sun.

One may be permitted to speculate upon the direction of progress during the next decade or two. Our advances will include the following:

(*a*) The continued accumulation of knowledge of the motions of stars at greater distances from the sun.

(*b*) Further studies of, and an explanation for, the mysterious *K*-term in radial velocities of early type stars.

(*c*) A firm knowledge of the total galactic motion of the sun from velocity studies of "external" objects (spiral nebulae).

(*d*) A marked increase in our knowledge of stellar movements perpendicular to the galactic plane.

(*e*) Steady improvement of our knowledge of galactic dynamics including star-streaming and other departures from the idealized model we presently employ and, finally, a better understanding of the complex organization we call the galaxy.

Dominion Astrophysical Observatory,
Victoria, B.C.
January, 1949.

THE SPECTRUM OF EPSILON AURIGAE, 1946-1948*

By K. O. Wright and Elsa van Dien

(With Plate I)

Abstract.—Equivalent widths of lines in ϵ Aurigae have been measured on moderately high-dispersion spectrograms (7.0 A./mm. and 4.4 A./mm.) in the region $\lambda\lambda$3700 - 6700. Turbulent velocities determined from curves of growth are found to vary with excitation potential, χ_i, for lines of Fe I, from about 20 km./sec. for $\chi_i = 0.5$ volts to 2 km./sec. for $\chi_i = 4.0$ volts; the large range in velocity, similar to the smaller effect found for α Persei, suggests that it is probably real. Excitation temperatures of 6200 ± 350°K. and 5500 ± 150°K. are found for ϵ Aurigae and α Persei, respectively. The effects of dilution of radiation in extended atmospheres are considered from the point of view of curve-of-growth phenomena. Small differences between lines arising from normal and metastable levels in Fe I suggest that dilution effects may be present in ϵ Aurigae. Line profiles in ϵ Aurigae are examined: they are so broad that instrumental distortion may be neglected. They could be produced by a rotational velocity of 30 km./sec. (assuming an unbroadened profile similar to that of lines in α Persei) or large-scale turbulent motions of 33 km./sec. of the type suggested by M. Schwarzschild. Either of these effects would mask small differences in line width which would correspond to the variations in turbulent velocity found from curves of growth.

Introduction

The system of ϵ Aurigae is one of the most interesting known. The light was discovered to be variable in 1821 by Fritsch[1] and it was shown to be an eclipsing system by Ludendorff[2] when he found that the radial velocity was that of the system at the time of mid-eclipse. Its period of 27.1 years is the longest of any known eclipsing system. The eclipse lasts nearly two years, of which nearly one year is total—from which data it may be shown that the densities are very low, of the order of 10^{-6} $\odot$. The depth of the eclipse,[3] $0^m.8$, suggests that the stars are not greatly different in brightness but the spectrum does not show the lines of the second star—it is nearly the same during the eclipse as at other

Contributions from the Dominion Astrophysical Observatory, No. 17.

[1]Müller, G. and E. Hartwig, *Geschichte und Literatur des Lichtwechsels*, vol. 1, p. 130, Poeschel and Trepte, Potsdam, 1918.

[2]*A.N.*, vol. 164, p. 81, 1904; *A.N.*, vol. 171, p. 49, 1906.

[3]Huffer, C. M., *Ap. J.*, vol. 76, p. 1, 1932.

times and the lines do not appear double when maximum velocity differences would be expected. The apparent contradictions in the results obtained for this system were reconciled in 1937 by Kuiper, Struve and Strömgren[4] who suggested that there is an almost grazing eclipse of the primary F2 star by a large infrared star having a shell of semi-transparent absorbing material which permits the lines of the F2 star to appear throughout the eclipse.

The spectrum of ϵ Aurigae has been studied since 1899 by many observers but particularly by those at the Yerkes Observatory. Its variations in radial velocity were studied first by Ludendorff[2] and later by Struve and Elvey.[5] There appear to be short-period fluctuations superposed on the long-period variation which led Ludendorff to supect the presence of a third body but, though a period of 110 days has been suggested, the results are not consistent with such a period; small variations in light synchronous with the radial-velocity variations have also been announced.[3,6]

The most recent eclipse occurred in 1928-30 and the spectrum was studied in some detail by Frost, Struve and Elvey.[7] They found that the broad lines, though usually symmetrical, became quite asymmetrical during the eclipse and in some cases, as noted by Adams and Sanford,[8] were even double. These asymmetries were observed some time before the partial phases of the eclipse and continued after it. They differed not only for lines of different elements but also for strong and weak lines of the same multiplet. The current explanation of the observed asymmetries is that they are produced by lines in the ionized shell of the infrared star.[4]

Observations

The observations discussed in the present paper were obtained between October 1946 and March 1948—a period well in advance of the next eclipse of 1955-57—at the suggestion of Dr. Otto Struve. They were made in order to study the apparent change of turbulent velocity, determined from curves of growth, with excitation potential

[4] *Ap. J.*, vol. 86, p. 570, 1937.
[5] *Ap. J.*, vol. 71, p. 136, 1930.
[6] McLaughlin, D. B., *Ap. J.*, vol. 79, p. 235, 1934.
[7] *P. Yerkes O.*, vol. 7, pt. 2, 1932.
[8] *P. A. S. P.*, vol. 42, p. 203, 1930.

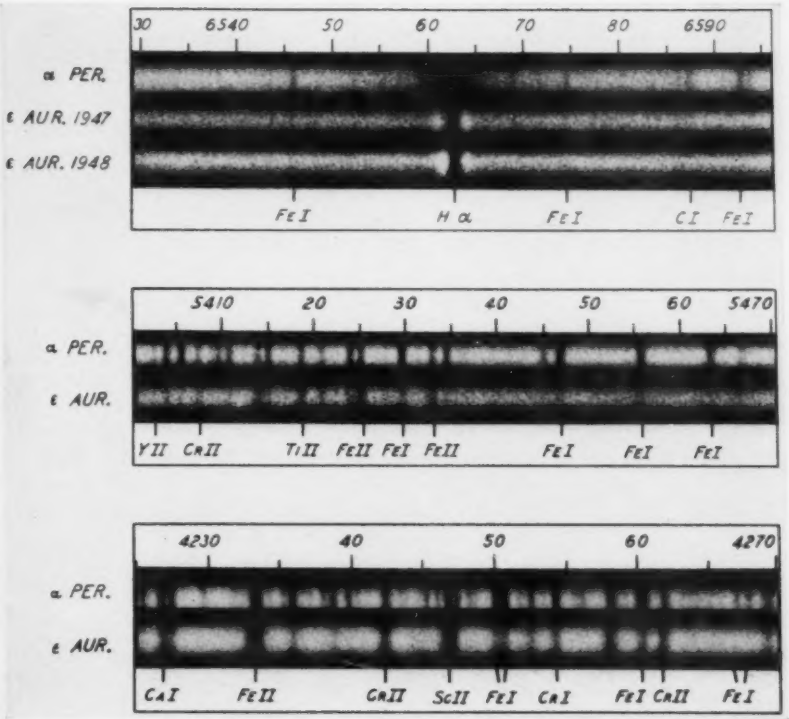

PLATE 1—Spectra of α Persei and ε Aurigae in the Regions λλ6530 - 6595, 5400 - 5470, and 4225 - 4270. The magnification in each case is very nearly 10 × the original spectrogram.

for lines of neutral iron; this effect had been observed for α Persei and other stars of class F.[9] ε Aurigae was chosen for a further study as Struve and Elvey[10] had found larger turbulent velocities for this star than for any other F-type star they observed.

The plates were obtained with spectrographs attached to the 72-inch telescope of this Observatory; most were obtained with the Wood grating mounted in the Littrow form[11] which gives a dispersion of 7.0 A./mm. from λλ4400 - 6800 in the second order and a dispersion of 4.4 A./mm. from λλ3700 - 4600 in the third order. Additional plates were taken with the three-prism spectrograph in the region λλ4000 - 5600 where the dispersion ranges from 4.8 A./mm. at λ4028 to 19.3 A./mm. at λ5601. Two, or more frequently three, spectrograms were studied for each of the above spectral regions* and intensitometer tracings of the entire spectrum were made using the instrument designed by C. S. Beals.[12] Profiles of all lines which could be identified from a comparison with tracings of α Persei were sketched on the sheets, due allowance being made for blends; the intensities were then measured with the planimeter and reduced to equivalent widths. It should be noted that the lines are broad and usually shallow and, particularly in the red region, it would have been difficult to make certain identification of very weak lines without the comparison tracings of α Persei. Intensities obtained from plates taken with grating and prisms agreed within the probable errors of the measurements and, in the region λλ4200 - 4800, agreed also with the intensities published by Struve and Elvey.[10] There are not sufficient plates to test the possibility that the intensities vary with the short-period radial-velocity variations but the general agreement obtained from plates taken at different times suggest that such an effect, if present, is quite small.

The Spectrum of ε Aurigae

In the analysis of the intensities we shall confine the discussion

[9]Wright, K. O., *J. R. A. S. Can.*, vol. 41, p. 49, 1947.

[10]*Ap. J.*, vol. 79, p. 409, 1934.

[11]Beals, C. S., R. M. Petrie and A. McKellar, *J.R.A.S.Can*, vol. 40, p. 349, 1946.

[12]*J.R.A.S.Can.*, vol. 38, p. 65, 1944.

*Details concerning the plates and intensities will be published in *P. Dom. Ap. O.*, vol. 8, in preparation.

to lines of Fe I. However a few general remarks concerning the spectrum of ε Aurigae and a comparison of its appearance with that of α Persei, a supergiant of class F5, seem desirable. The spectrum is characterized by very broad absorption lines which were ascribed by Struve and Elvey[10] to turbulent motions in the atmosphere—the lines are about twice as wide as those in the spectrum of α Persei. Plate I shows three representative regions of the spectrum: λλ6530 - 6590, 5400 - 5470, and 4225 - 4270. The top section shows that Hα appears in emission in ε Aurigae though it is a normal absorption line in α Persei; Adams and Sanford[8] noted this fact on plates taken at the time of the 1928-30 eclipse but at that time there was only one emission component about one angstrom to the red of the absorption line. Here an emission line appears on each side of the absorption line and the suggested explanation that the differences are produced by the radial-velocity motion of the absorption line superposed on a broad stationary emission line is not completely satisfied by the spectrogram marked ε Aur., 1947 (actually taken December 16, 1946) where one weak emission line is displaced more than an angstrom to the violet.

Of other light elements observable in the region covered by the spectrograms, O I is considerably stronger in ε Aurigae than in α Persei, C I is clearly present, N I is probably present, and S I is also present, though not as strong as in α Persei. The neutral lines of other atoms commonly present in F-type spectra are much weaker in ε Aurigae than in α Persei and those of Ti I and V I cannot be identified with certainty in the region studied. The ionized lines of these elements are considerably stronger than in α Persei due, no doubt, to the extensive low-pressure atmosphere. These effects are shown well in Plate I but are even more evident on the intensity tracings shown in figure 1 since the broad lines in ε Aurigae are often difficult to see on the spectrogram though readily identifiable on the tracing. The lines of Fe I are quite weak in the red and green regions of the spectrum but lines easily seen in α Persei can usually be found in ε Aurigae; on the other hand, however, it should be noted that the total absorptions of the strongest Fe I lines in the ultraviolet region are actually stronger than those of the same lines in α Persei. This effect could be due to a different variation of the continuous absorption coefficient with

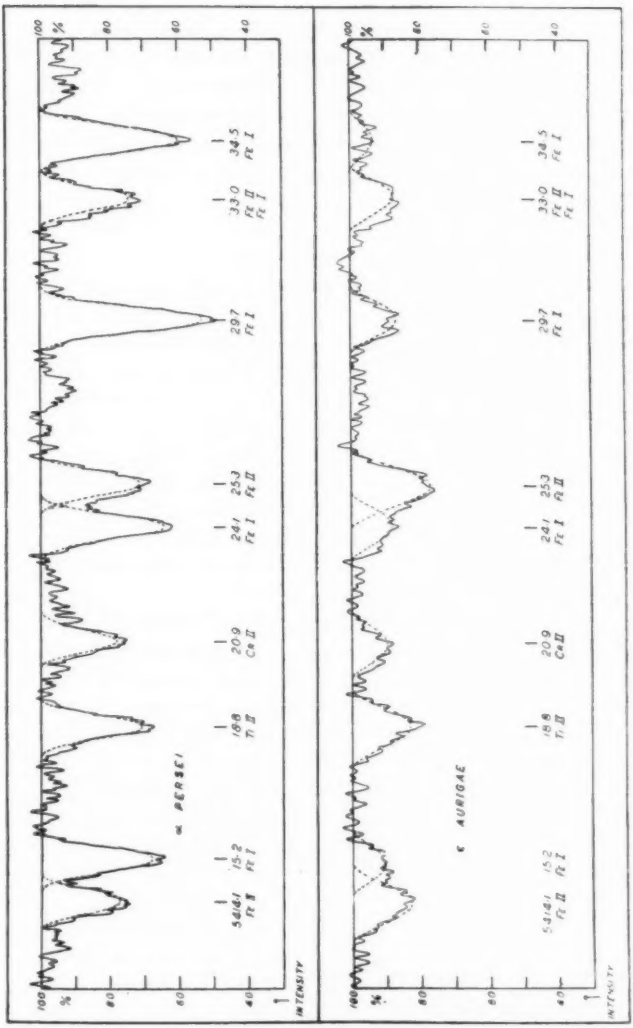

FIG. 1.—Intensitometer Tracings of α Persei and ε Aurigae in the Region λλ5412 - 5437. The features illustrated in Plate I are more clearly shown in the tracings. The lines in the spectrum of ε Aurigae are broader, the equivalent widths of ionized lines are greater and those of neutral lines are less than in α Persei.

wave-length or to an effect similar to that noted in the sun where lines in the red are weaker than those in the violet because we see down deeper into the atmosphere in the violet. Goldberg and Pierce[13] indicate that the number of effective absorbers producing a line in the violet is twice that in the red portion of the solar spectrum. However in this paper we shall consider the results only in terms of the simple theory of the curve of growth.

Curves of Growth

In a previous note[14] preliminary curves of growth for ϵ Aurigae were discussed and a turbulent velocity of 16 km./sec. was derived from lines of Fe II, Ti II and Cr II. Curves obtained from lines of Fe I suggested that the turbulent velocity, v_*, varied with excitation potential, χ_i, from 15 km./sec. for $\chi_i = 0$ volts to 7 km./sec. for $\chi_i = 2.5$ volts. The results were not completely satisfactory since weak lines showed a large scatter and the curve was not always well-defined. Since that time the intensities have been improved considerably by the addition of new observations and a complete re-examination of the tracings with particular attention being paid to the position of the continuous background of the spectrum.

As noted in earlier *Contributions*[9,15], the curve of growth gives information concerning important properties of a stellar atmosphere since it relates the observed intensity of an absorption line to the number of atoms in the atmosphere which produces it. In a curve of growth $\log W/\lambda$ is plotted against $\log X_f$ where W, the equivalent width, is a measure of the total energy absorbed from the continuous background of the spectrum. λ is the wave-length and X_f, by definition, is the optical depth at the centre of the line but, as determined here, is an empirical quantity obtained from an observed curve of growth for the sun.[16] Each line is represented by a single point on a graph and a series of observations is fitted to a theoretical curve of growth with ordinate $\log (W/\lambda \cdot c/v)$ and abscissa $\log X_*$

[13]O.N.R. Project M720-5, October 1947, Ann Arbor.

[14]Wright, K. O., *P.A.S.P.*, vol. 59, p. 171, 1947.

[15]Wright, K. O., *J.R.A.S.Can.*, vol. 40, p. 183, 1946.

[16]Wright, K. O., *P. Dom. Ap. O.*, vol. 8, p. 76, 1948; *Ap. J.*, vol. 99, p. 249, 1944.

plotted to the same scale on another graph. The relative shift between the two graphs along the ordinate is then log c/v, where c is the velocity of light and v, the turbulent velocity; that along the abscissa is log X_*/X_f which represents the number of atoms in a given stage of ionization relative to the sun and also includes a temperature factor.

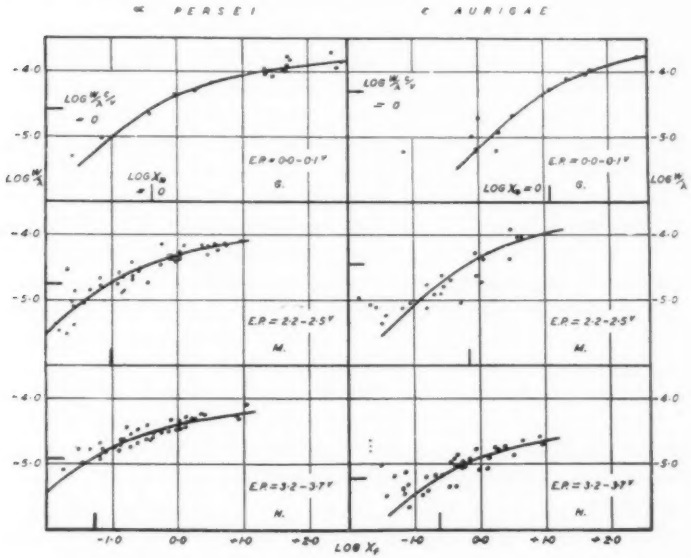

FIG. 2.—Curves of Growth for α Persei and ϵ Aurigae for Fe I Lines of Different Excitation Potentials. Theoretical curves based on the Schuster-Schwarzschild model have been superposed in the position to fit the observations best. The positions corresponding to $\log \frac{W}{\lambda} \cdot \frac{c}{v} = 0$ and $\log X_* = 0$ of the theoretical curve have been indicated in each diagram.

Since the number of atoms of a given element having electrons in a given energy level depends on the temperature, which must be determined later, all lines of Fe I were separated into groups, each having a range of about half a volt in excitation potential and each group was plotted separately. Sample plots of these observations

are shown in figure 2 for α Persei and ε Aurigae, revised data being used in each case. The solid line represents the theoretical curve of growth fitted as well as possible to the observations; the positions of log $(W/\lambda \cdot c/v) = 0$ and log $X_* = 0$ have been indicated on each diagram. The displacements in terms of turbulent velocity, v_*, and log $X_* v_*/X_f$ are listed in Table I.

The theoretical curve shown in figure 2 is that based on the so-called Schuster-Schwarzschild model of a stellar atmosphere as computed by Menzel[17] and by Unsöld.[18] This model postulates a continuously radiating surface, the photosphere, upon which is superposed a reversing layer which produces the absorption lines; another way of describing this model is that the ratios of the line-absorption and line-scattering coefficients to the continuous absorption coefficient decrease very rapidly as we go below the surface of the star. A second model described by Milne and Eddington assumes that these ratios are constant with depth, i.e., there is no sharp dividing line between photosphere and reversing layer; Pannekoek and van Albada[19] and Strömgren[20] have computed curves of growth for certain conditions which apply to this model. Although it is unlikely that either model represents exactly conditions in stellar atmospheres, it seems probable that the Milne-Eddington model better represents conditions under which most solar lines are produced. Greenstein[21] has compared data computed for each model and finds that the observed value of the damping constant agrees better with that for the Milne-Eddington model than that for the Schuster-Schwarzschild model. Differences between the two models are most pronounced on the damping part of the curve of growth, which is not well-determined by the present observations. The latter can be made to fit either type of curve equally well and, though the numerical values of the turbulent velocities are slightly different, the differences noted in this paper do not depend upon the particular model employed.

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[17] *Ap. J.*, vol. 84, p. 462, 1936.
[18] *Physik der Sternatmosphären*, p. 264, Springer, Berlin, 1938.
[19] *P.A. Inst.*, Amsterdam, vol. 5, pt. 2, 1946.
[20] *Festschrift fur E. Strömgren*, p. 126, Munksgaard, Copenhagen, 1940.
[21] *Ap. J.*, vol. 107, p. 151, 1948.

The fit of the observations on the theoretical curve for each range in excitation potential has been indicated by the weight listed in the last column for each star in Table I. From figure 2 it is seen immediately that the observations show considerably less scatter for α Persei than for ε Aurigae and this is reflected in the weights. The data upon which this paper is based, namely the positions where a series of observations fits a smooth curve with a slope which changes relatively slowly, are extremely difficult to determine accurately. However the settings have been repeated several times by each author and the agreement is reasonably satisfactory; for α Persei the greatest total range in log c/v is 0.19 and in log X_*/X_f is 0.36 for five settings made with each graph, completely independently and at different times; for ε Aurigae the range in log c/v for $\chi_i = 2.81$ is 0.39 and for $\chi_i = 3.52$ is 0.30 but for the remaining eight groups the greatest range is 0.23; in log X_*/X_f these values are 0.83, 1.03, and 0.64 respectively. For each of the discordant plots, the range in log X_f for lines with log $W/\lambda = -5.4$ (i.e., $W \sim 0.02$ A.) is 1.0 or more and the position of best fit is somewhat indeterminate.

TABLE I.—CURVE-OF-GROWTH DATA DERIVED FROM LINES OF FE I

E.P.	Level	ε Aurigae					α Persei				
		v_*		$\log \frac{X_* v_*}{X_f}$		Wt.	v_*		$\log \frac{X_* v_*}{X_f}$		Wt.
		S.-S.	M.-E.	S.-S.	M.-E.		S.-S.	M.-E.	S.-S.	M.-E.	
volts		km./ sec.	km./ sec.				km./ sec.	km./ sec.			
0.05	G.	16.7	16.5	5.00	5.42	2	8.3	8.0	6.32	6.76	2
0.96	M.	22.2	26.4	4.93	5.32	2	6.1	7.3	6.54	6.80	2
1.54	M.	9.2	10.6	5.68	5.97	1	7.3	7.4	6.53	6.88	2
2.26	Q.	4.7	4.3	5.51	5.85	1	4.9	5.8	6.76	7.11	3
2.80	Q.	4.8	4.6	5.68	6.20	1	3.3	4.5	6.86	7.14	2
3.52	Q.	3.7	5.2	6.22	6.28	1	2.9	3.2	6.77	7.14	2
2.87	N.	4.2	7.0	5.42	5.59	2	3.9	4.3	7.00	7.34	2
3.40	N.	1.7	2.7	5.73	6.00	2	3.6	4.0	6.81	7.16	3
4.12	N.	1.1	1.4	6.22	6.46	1	4.1	4.9	6.88	7.23	3
4.50	N.	1.5	2.1	6.17	6.39	1	3.9	4.3	6.88	7.27	3

The velocities listed in Table I cannot be considered constant. In a previous paper[9] a similar range in velocity for α Persei derived from less extensive data was considered real. Since ε Aurigae was chosen as a test object where this effect, if real, might be expected to be greater, the present results may be taken to confirm its existence, for the total range in velocities is greater than for α Persei and again the velocities decrease with increasing excitation potential. The principal discordant velocity, that for $\chi_i = 0.96$ volts, is derived chiefly from strong lines in the ultraviolet where blends tend to increase the measured strength of the lines and, since they lie on the transition portion of the curve of growth, to increase the velocity.

It has been suggested that the effect is produced by combining intensities of lines situated in different parts of the spectrum—since the strong lines of lower excitation potential are concentrated more in the violet and the weaker lines of higher excitation potential tend to occur in the red region of the spectrum. In order to test this possibility, plots were made for lines in the region λλ5200 - 5800 which contains both strong and weak, unblended lines. The results for ε Aurigae, the mean of three fittings, are:

χ_i volts	v km./sec.
0.96	4.0
3.41	2.1
4.52	1.7

The absence of the strongest lines in the violet combined with the scatter inherent in observations of weak lines changes the result completely for $\chi_i = 0.96$ volts, but the trend that the velocity decreases with increasing excitation potential remains the same. However it should be noted that by combining the results over the whole spectrum from λλ3700 - 6700 the strongest lines of each excitation potential have been measured, while the weakest lines measured have been limited only by the difficulty of distinguishing

*In all cases where empirical Xf-values are used, it is assumed that all lines in the solar spectrum can be fitted on the single curve of growth determined from lines of TiI and FeI. Recent work of Pierce and Goldberg (O.N.R. Project M720-5, August 1948, Ann Arbor) as well as that of King and Wright[22] suggests that a single curve of growth for the sun may not be satisfactory. More laboratory f-values are urgently needed to check this point.

them from the continuous background of the spectrum. Under the circumstances, the results must be viewed with some caution, especially since there may be a real variation of the continuous absorption coefficient with wave-length. However the magnitude of the effect and the fact that it is greater for ϵ Aurigae than for α Persei lead the authors to believe that it is probably real.*

The explanation of the effect in terms of a real decrease of turbulent velocity with increasing excitation potential is not completely satisfactory. A year ago the authors made an attempt to explain the relative shift along the log W/λ-axis in terms of departures from thermodynamic equilibrium and a resulting non-Boltzmann distribution of the atoms in the various energy levels. Though the results seemed encouraging at first, there were serious objections to the theoretical discussion involved and, though it may prove possible to consider the problem again, it is not carried further at this time.

If the literal explanation in terms of velocities in the atmosphere is correct, then it would seem that there is a considerable stratification in the atmosphere, even for atoms of the same element and also that the turbulent motions are greater in the layers where the strong lines of low excitation potential arise than in those producing the weak lines of high excitation potential. This may again be related to the observations of the flash spectrum of the sun, for the arcs of strong lines are longer (i.e., extend higher above the photosphere) than the weak lines and it is known that velocities derived from the widths of lines in prominence spectra are greater than those derived from spectra of the reversing layer. This same effect was thought to have been found in the solar spectrum for lines of V I[22] when curves of growth were obtained by combining measures of line intensities from the Utrecht *Photometric Atlas of the Solar Spectrum*[23] with the laboratory *gf*-values measured by R. B. King.[24] However two recent discussions of the solar curve of growth[13,25]

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[22]King, R. B. and K. O. Wright, *Ap. J.*, vol. 106, p. 224, 1947.

[23]Minnaert, M., J. Houtgast and G. F. W. Mulders, Schnabel, Kampert, and Helm, Amsterdam, 1940.

[24]*Ap. J.*, vol. 105, p. 376, 1947.

[25]Menzel, D. H. and Barbara Bell, O.N.R. Project M720-5, June 1948, Ann Arbor.

have suggested that the apparent variation of turbulent velocity with excitation potential may be removed by taking account of the variation of the continuous absorption coefficient with wavelength. A further investigation of this point seems desirable.

Excitation Temperatures

In a previous *Contribution*,[9] it was noted that if there is a variation of turbulent velocity with excitation potential, the excitation temperature can still be obtained according to the formula

$$\log \frac{X_* \, v_*}{X_f \, v_\odot} = D - 5040 \, \chi_i \left(\frac{1_*}{T_*} - \frac{1}{T_\odot} \right)$$

where the subscripts $_*$ and $_\odot$ refer to the star and sun respectively, and T is the excitation temperature; D is a constant proportional to the number of atoms in the star and sun.

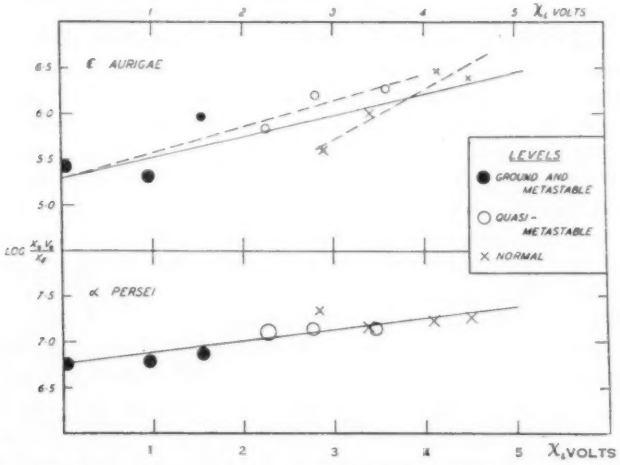

FIG. 3.—Excitation Temperatures of ϵ Aurigae and α Persei. The solid line, representing all observations, corresponds to a temperature of 6200 ± 350°K. for ϵ Aurigae and 5500 ± 150°K. for α Persei. The dashed lines represent the observations from metastable and normal levels respectively.

The values of log $(X_* \, v_*/X_f)$ have been included in Table I for each excitation potential; the quantity $v_\odot$, which may be taken as

1.6 km./sec., is assumed to be a constant and has been omitted since only relative values of D are used. The data, fitted to the Milne-Eddington curves of growth have been plotted in figure 3. The best straight lines through points, shown as solid lines in the figure, have been determined from least-squares solutions. The slopes are inversely proportional to the excitation temperature and, taking $T_* = 4850 \pm 125$°K. for Fe I, the excitation temperature of ϵ Aurigae is found to be 6200 ± 350°K. and that of α Persei is 5500 ± 150°K; the latter value may be compared with that of 5350 ± 125°K. found previously.[9]

It may be noted that a rough estimate of the relative numbers of atoms in these atmospheres may be obtained by comparing the values of D—which are found to be 5.30 for ϵ Aurigae and 6.76 for α Persei. This calculation indicates that there are nearly thirty times as many Fe I atoms in α Persei as in ϵ Aurigae. Although this approximation assumes a *static* atmosphere, the results should be of the correct order of magnitude for, though the atmosphere of ϵ Aurigae is probably more extensive than that of α Persei, there are probably fewer atoms of Fe I present since the lower pressure is favourable to higher ionization; hence most of the iron atoms will be ionized and appear as Fe II—the lines of which are very prominent in the spectrum of ϵ Aurigae.

Dilution of Radiation in the Atmosphere of ϵ Aurigae

In stars with extended atmospheres such as ϵ Aurigae, detailed studies of curve-of-growth phenomena may indicate the presence of diluted radiation. At great distances from the surface of a star which radiates like a black body at temperature T, the energy density will be less than the equilibrium value for the same temperature. Studies by Rosseland,[26] Struve and Wurm,[27] and Struve,[28] among others, have shown that the population of normal highly-excited atomic energy levels will be decreased by an amount proportional to the so-called "dilution factor" which is a measure of the departure of the energy density from its equilibrium value. On the other hand the population of metastable levels, where

[26] *Ap. J.*, vol. 63, p. 218, 1926.
[27] *Ap. J.*, vol. 88, p. 93, 1938.
[28] *Pr. Am. Phil. Soc.*, vol. 81, p. 211, 1939.

downward spontaneous transitions are forbidden, is not affected by dilution to any great extent. Thus, in such a star, lines arising from metastable levels are relatively stronger than "normal" lines produced by the same atom. Of the two stars considered in this paper, the spectrum of α Persei appears to be normal but that of ε Aurigae shows Hα in emission, which suggests an extended atmosphere somewhat similar to the emission-line shell stars of earlier spectral types. Struve[28] noted that it might be possible to detect dilution effects in ε Aurigae from a detailed study of its curve of growth.

The spectrum of Fe I fulfills, in part, the conditions required for a study of dilution effects derived from the curve of growth: it has many lines covering a wide range in intensity and the lines arise from both metastable and normal levels. The analysis of the spectrum has been completed by Russell and Moore[29] for the region λλ1850—12,000. The lowest odd level which has strong intercombination lines with the ground, even level, a^5D, is z^7D° with $\chi_i = 2.4$ volts; hence levels below this must be classed as metastable. Above this level transitions are observed between most levels which, accordingly, are classed as normal. However, no transitions were observed between certain levels in the region covered by Russell and Moore; these were classed as metastable originally but in a private communication* Dr. Russell suggested that there might well be transitions in the far infrared which have not been observed; therefore they have been classed as quasi-metastable levels. Curves of growth were constructed for the various types of levels as listed in Table I, column 2, where the symbols G for ground, M for metastable, Q for quasi-metastable and N for normal levels are used.

If, for the purposes of the present discussion, the first three types are considered together, an examination of figure 3 indicates that, for ε Aurigae, the distribution of these points is different from that for the normal points; for α Persei, any departures from the straight line corresponding to $T = 5500°$K. cannot be considered significant. In order to test the reality of these differences for ε Aurigae, least-squares solutions were made for each set of points;

[29] *Tr. Am. Phil. Soc.*, vol. 34, pt. 2, 1944.

*The authors wish to express their thanks to Dr. L. H. Aller who discussed this point with Dr. Russell.

the best straight lines, indicated by dashes in the figure, correspond to $T = 6650 \pm 450°K.$ for the metastable levels and $10{,}250 \pm 1600°K.$ for the normal levels. These solutions may have some significance since the probable errors are less than the differences but there is considerable uncertainty in fitting the plots to theoretical curves of growth. It is probably more noteworthy that all the normal points (denoted by X's) lie below the line drawn through the metastable points. This result supports the hypothesis of the presence of diluted radiation in the atmosphere of ϵ Aurigae since the number of atoms (which is proportional to the intercept along the ordinate) seems to be appreciably greater for the metastable levels than for the normal levels; if the velocity factor is omitted and log (X_*/X_f) is plotted against χ_i, the same effect is observed though to a less marked degree.

Line Profiles in ϵ Aurigae

If the variation of turbulent velocity with excitation potential is real, there should also be a variation of line width with excitation potential. If the profiles are produced by random thermal and turbulent motions, the line-shapes may be assumed to follow a Gaussian distribution and velocities may be determined from the half-width according to Unsöld's formula,[30]

$$v = \frac{2\Delta\lambda}{\lambda} \frac{c}{1.66}$$

where $2\Delta\lambda$ is the total width of a line at the point midway between its centre and the continuum. Table II gives the results of measurements made on sixty-six lines on second and third order grating spectra. No correlation between excitation potential and mean velocity is found. The very few strong lines give a higher value for the velocity than the weaker lines but most striking is the very high random velocity of all lines, which ranges between 30 and 35 km./sec.—considerably higher than the values found from the curves of growth. This result is somewhat similar to that found by Struve[31] in the spectrum of δ Canis Majoris but there the strong lines are considerably broader than the weaker lines.

[30] *Physik der Sternatmosphären*, p. 158, Springer, Berlin, 1938.

TABLE II—VELOCITIES CALCULATED FROM LINE WIDTHS IN ϵ AURIGAE

E. P. volts	Velocity Km./sec.	Number of Lines
0.0-0.1	30.1	3
0.8-1.0	33.8	17
1.4-1.6	33.2	6
2.6-3.0	34.6	3
3.2-3.7	33.0	13
3.7-4.2	31.7	24

For a further study of line profiles, spectra were obtained with the second order of the grating from λλ5400 - 5550, the region being chosen to include numerous unblended lines of considerable strength. Farther to the violet, blending effects and uncertainties in the position of the continuous background make the observed line shapes less trustworthy in spite of the somewhat higher dispersion available with the third order. In order to test the effect of the spectrograph on the line profiles, spectra were obtained of a discharge tube which was kindly loaned by Professor A. M. Crooker of the University of British Columbia. The mean profile of seven argon emission lines in the region near λ5500 is shown as the narrowest profile in figure 4; it is shown inverted for comparison with the other data.

All the lines of ϵ Aurigae are very wide and most are relatively shallow. Over the region covered, the width was found to be almost independent of wave-length, atomic weight, or excitation potential, though lines of Fe I, Fe II, Ti II, Cr II, and Sc II were measured. Since the shapes of all lines agreed very closely, a mean profile is shown in figure 4. As the instrumental profile has a half-width less than one-third that of ϵ Aurigae, the influence of the spectrograph can safely be neglected. The line profile does not agree with any of the Voigt profiles given by van de Hulst and Reesinck;[32] however that part of the line with depth $\geq$ 60 per cent can be represented satisfactorily by a Gaussian curve corresponding to a turbulent

[31] *Ap. J.*, vol. 104, p. 138, 1946.
[32] *Ap. J.*, vol. 106, p. 121, 1947.

velocity of about 33 km./sec. The theoretical curve shows stronger wings than are observed in the stellar spectrum.

Line profiles of similar lines in α Persei were also obtained for comparison with those of ε Aurigae. However, since the lines are considerably narrower, the effect of the spectrographic distortion cannot be neglected. The mean profile is also shown in figure 4 and is used in the discussion below.

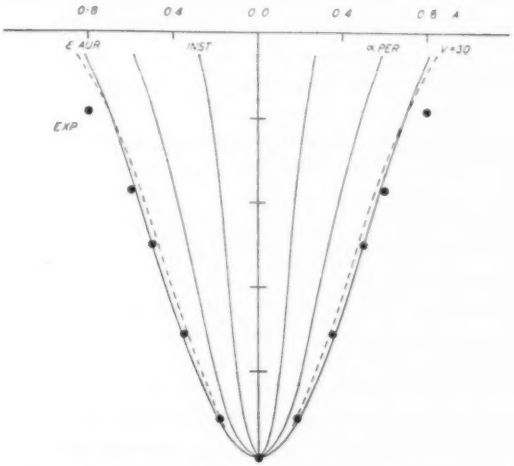

FIG. 4.—Observed Line Profiles for ε Aurigae and α Persei in the Region λλ5400 - 5550. The solid lines, in the order of increasing width, represent mean profiles obtained from argon emission lines, α Persei and ε Aurigae. For the observed profiles the central intensity, the mean of all lines measured, is 65 per cent of the continuous background for α Persei and 76 per cent. for ε Aurigae; the lines have all been drawn on the same scale for comparison purposes. The dashed line represents a line in the spectrum of α Persei broadened by a rotational velocity of 30 km./sec. The dots correspond to a Gaussian distribution with a velocity of 33 km./sec.

The shape of the lines in ε Aurigae is suggestive of rotation, which is considered to be the chief source of broadening in the spectra of many early-type stars. Since turbulent motions seem

[33]Details and references are given in *Cont. Dom. Ap. O.* No. 14, *J.R.A.S.Can.*, vol. 42, p. 249, 1948.

to be present in both stars—as indicated from the curves of growth—the theory of rotational broadening[33] was applied to the lines of α Persei, assuming a uniform disc, to see if the observed shape of lines in ϵ Aurigae could be produced. Reasonable agreement with the observed profiles for ϵ Aurigae was obtained for a rotational velocity of 30 km./sec.; the small remaining differences could plausibly be ascribed to limb darkening, to the larger turbulent motions in ϵ Aurigae or to some additional unknown differences in physical conditions in the stars. In this connection it should be mentioned that the deviations of the radial-velocity observations at the 1928-30 eclipse from the mean radial-velocity curve[4] are very suggestive of departures due to rotation effects. However in a private communication, Dr. Struve has expressed the opinion that the asymmetries in the lines are caused by the passage of the light of the F-star through the outer regions of the infrared star, though a rotational velocity of 30 km./sec. is not excluded by the observations. From the data on dimensions given by Kuiper, Struve and Strömgren[4] it was found that the gravitational acceleration at the surface of ϵ Aurigae is about forty times the centrifugal acceleration required to maintain a rotational velocity of 30 km./sec.; thus rotation is not impossible from the dynamical point of view.

M. Schwarzschild[34] has put forward the suggestion that the discrepancy between line widths observed in his studies of η Aquilae and turbulent velocities from curves of growth could be explained in terms of large-scale jets in the atmosphere. The size of these jets would be such that light from the star reaching the observer passes through only one instead of through a large number as is the case in the small-scale turbulence considered by previous investigators.[35] In the simplified case where the disc is covered with radial jets moving inward and outwards with one velocity, v_0, it is easily proved that the line profiles will be broadened in exactly the same way as by the rotation of a uniform disc with equatorial velocity, v_0; in each case a radial velocity $v_0 \cos i$ has the weight $\sin i$ in contributing to the line shape. Hence what has been interpreted

[34]Schwarzschild, M., B. Schwarzschild and W. S. Adams, *Ap. J.*, vol. 108, p. 207, 1948.

[35]See. e.g., Allen, C. W., *Ap. J.*, vol. 85, p. 165, 1937; Unsöld, A., loc. cit., p. 272; Redman, R. O., *M.N.*, vol. 104, p. 102, 1944.

as rotation here could after all be a large-scale turbulence.

R. N. Thomas[36] has considered the possibility of superthermic jets, with velocities of 30 km./sec. in the solar atmosphere, being related to the chromospheric spicules. However he infers that the motions must be thermal in origin; though for hydrogen atoms, a velocity of 33 km./sec. corresponds to a temperature of 66,000°K., for iron atoms, it corresponds to a temperature of 3.7×10^6°K., In a very extensive atmosphere such as that of ϵ Aurigae it does not seem that such motions need be thermal or produced by collisions and therefore his arguments do not rule out the possible presence of such jets.

Miss Anne Underhill[37] has recently made calculations which compare the shapes of lines formed in a plane-parallel atmosphere and in an extensive atmosphere where the curvature of the outer layers is allowed for. She has found that in the latter case the centres of the lines are shallower and the wings are stronger. This difference is similar to that noted between the observed profiles of lines in ϵ Aurigae and in α Persei. As the atmosphere of ϵ Aurigae must be very extensive, it may be that the curvature of the atmosphere should be considered, though no further calculations are made at this time.

Thus it would appear that the broad lines in the spectrum of ϵ Aurigae could be produced either by rotation or by large-scale jet motions superposed on the small-scale turbulence indicated by the curves of growth. In either case the larger motions would be the principal factor in broadening the lines and any differences in turbulent velocity found from the curves of growth might be very difficult to detect in the presence of the larger phenomenon.

Dominion Astrophysical Observatory
Victoria, B.C.
October 1948.

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[36] *Ap. J.*, vol. 108, p. 130, 1948.
[37] *Ap. J.*, vol. 107, 247, 1948.

STAR DIAGONALS ON FINDER TELESCOPES

By F. K. Dalton

Anyone who has manipulated an astronomical telescope to enable a queue of spectators to view the wonders of the heavens will realize that a diagonal on the finder telescope would be of great convenience in preventing interference with the observers while keeping the instrument directed at the celestial bodies. It would be more satisfactory for both demonstrator and spectators.

A star diagonal usually includes a right-angle prism as the reflecting element. This type of prism must be located in the optical system where it receives rays which are essentially parallel or where the angle of convergence, or divergence, is small. It invariably is placed between the objective lens, or parabolic mirror, and the eyepiece. Finder telescopes are usually of quite simple design, without any particular means for focussing except that the eyepiece may be slipped axially, or turned, in the receiving tube. No provision has been made for the insertion of any device, except the cross-wires or reticule, between the objective lens and the eyepiece.

If one wished to redesign his finder telescope, he could incorporate the necessary diagonal details but he could not then revert readily to his original finder arrangement,—a feature which it may be desirable to retain. To design a suitable star diagonal for attachment to the existing finder telescope therefore presents certain problems. The writer has tried several methods and is recording the results of his experiments here for the guidance of those who may wish to apply diagonals to their present finders.

The External Prism

Probably the first idea which comes to mind is to place the diagonal prism between the eyepiece and the eye, external to the finder telescope, to turn the rays out in a direction convenient to the demonstrator. This method, however, presents two problems, namely, the eye must be farther from the eyepiece than usual,

which reduces the field of view, and, also, the angle of incidence, at the reflecting surface of the prism, of the rays from certain areas or objects viewed is less than the critical angle of reflection for glass so that in part of the field the prism does not give total reflection. Only a very small percentage of those rays which reach, and should appear to come from that area, will be reflected, as shown in figure 1. Furthermore, if the prism be so mounted that rays can enter it through the hypotenuse face, these rays will interfere with the weak reflections from this area.

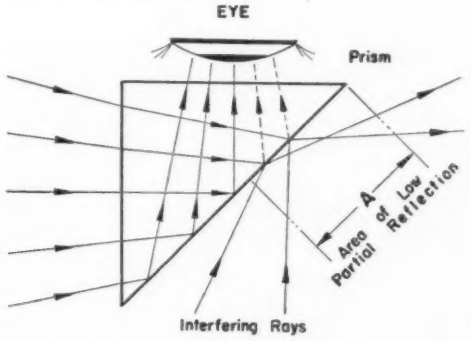

FIG. 1—*Low Partial Reflection in the Right-Angle Prism.* With the eye close to the prism, only low partial reflection is obtained in the area, "A". Also, rays from the rear may enter the hypotenuse face of the prism in this area and seriously interfere with the image.

It would appear that the first of these problems could be solved satisfactorily by a new eyepiece giving long eye relief, as used in telescopic sights for firearms, i.e., an eyepiece which allows the eye to be at some distance back from the rear of the sight. This also may help appreciably in solving the second problem or, at least, in reducing its seriousness and inconvenience; for the farther from the eyepiece that the eye is required to be, the more nearly parallel the rays would be, and the smaller field may eliminate the area of low partial reflection. On the other hand, once the object is centered in the finder, the only requirement may be to keep it there so a reduced field may not be a serious handicap provided it covers the centre of the reticule.

The Diagonal Eyepiece

To find a suitable location in the optical system for the reflecting element is really the whole problem,—to "find a way or make it,"—and it may be necessary to change the optical arrangement to provide such a location. One such method which the writer can recommend quite highly is the lengthening of the eyepiece, by spacing the eye lens and field lens farther apart to make room for a prism reflector between them. This will require an eye lens of longer focal length, which slightly reduces the mangifying power of the eyepiece.

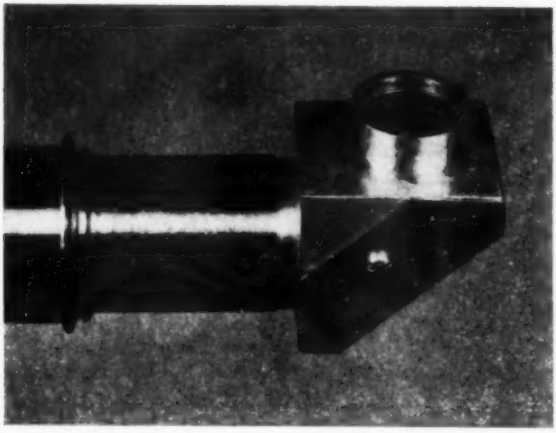

Fig. 2—*The Diagonal Eyepiece.* This eyepiece, shown attached to the finder telescope, consists of field lens, Amici roof prism and eye lens, and may be turned to any desired position. It gives a fully erect image and the full field of view of the finder. Its compactness is of considerable advantage.

The ordinary right-angle prism is not satisfactory as the reflecting element, however, for here again it will give an area of low partial reflection. It becomes necessary then to use an Amici roof prism to avoid this difficulty. The results obtained with this arrangement are then very good. The eye end of the writer's finder telescope is shown in figure 2, with the new diagonal eyepiece in position. It will be noted that this new device is virtually streamlined to the finder; the eye lens does not project appreciably

outward and therefore is not in the way. It may be of interest that this diagonal eyepiece gives a fully erect image but the astronomer, either professional or amateur, is not usually much concerned as to whether the image be inverted or erect in the finder. The full field of view of the finder is retained, and the magnifying power is about 88 per cent. of that obtained with the original direct eyepiece.*

Reformation of Image

Another method of providing a location for a prism is to add an erecting system to the finder thus lengthening the optical axis. By means of erecting lenses a combined image of reticule and object is formed and a positive eyepiece, consisting of a single lens, will magnify this image.

This method allows the use of the ordinary right-angle prism and gives long eye relief, the eye being about three inches from the eye lens, but it reduces the field of view, from five degrees to less than two degrees and the resulting attachment is not nearly as neat as the diagonal eyepiece. The long eye relief is, of course, of advantage in that the demonstrator can merely glance at the eyepiece, without fitting his eye to it, and can see the images of the reticule and celestial objects through a relatively wide angle of position of the eye.

Conclusion

From the writer's experiments, the diagonal eyepiece appears to be the most satisfactory and most convenient arrangement. Incidentally, this eyepiece does give a good measure of eye relief, should the demonstrator require it. It also will give the full field of view and this is a very desirable feature in case the telescope accidentally be moved far off the object while showing the celestial bodies to enthusiastic spectators.

20 Wilgar Road,
Toronto, 18, Ontario.

*Where one is searching for an object in the sky by first locating its position on a star map in a pattern of readily visible stars, he will find the erecting feature of considerable advantage in that the star pattern appears in the finder just as he sees it on the star map,—not inverted nor even turned over on one axis,—and therefore it is more easily identified than when either the ordinary eyepiece or right angle prism is used.

COMMUNICATIONS
FROM THE
DAVID DUNLAP OBSERVATORY
Number 18

TWO RV TAURI-TYPE VARIABLES IN GLOBULAR CLUSTERS*

By Helen B. Sawyer

(with Plate II)

THE RV Tauri type of variable star is characterized by slow light changes, a range of one or two magnitudes, and a light curve with deep and shallow minima alternating. It takes more than two months for the star to go through the complete cycle of its light changes.

Brief discussions of this type of star with light curves have been given by Payne-Gaposchkin and Gaposchkin in *Variable Stars,* 1938, and more recently by Campbell and Jacchia in *The Story of Variable Stars,* 1941. At the time these books were written, the RV Tauri stars numbered only two dozen and were considered a rare type. They are still not regarded as common, but as better light curves are obtained for variables whose periods are over one month but less than four months, more light curves are found to exhibit the RV Tauri characteristics. The new Russian *Catalogue of Variable Stars* by Kukarkin and Parenago, Moscow, 1948, with 10,912 variables, lists 72 in the RV Tauri group. It is not easy to prove that a variable is of this type, as a series of observations over at least two months of time, on nights as close together as possible, is necessary to show the character of the light curve. Naturally, bright moonlight and cloudy skies are apt to make breaks in the observations at critical points.

Extended series of observations over recent years now indicate that two variable stars in globular clusters for which I have previously published tentative periods can best be assigned to the RV Tauri

*Paper presented at the meetings of the American Astronomical Society, New Haven, Conn., December, 1948.

class, and the former periods approximately doubled. These two stars are Chèvremont's variable in Messier 2 in Aquarius, (NGC 7089), and Sawyer's variable No. 6 in Messier 56 in Lyra (NGC 6779).

1. Chèvremont's Variable in Messier 2.

As the name of this star indicates, it was discovered by the French observer Chèvremont in 1897,[1] when he carefully compared visually the appearance of the cluster in a 5-inch telescope with a drawing made by Flammarion[2] some years earlier. He detected that the brightest star within the confines of the cluster was absent from Flammarion's drawing, and after some nights of watching, concluded that he had found a new variable star. The star is of very high absolute magnitude, about −3.5 at maximum, and its light fluctuations from apparent magnitude 12.5 to 14.0 strikingly alter the appearance of the cluster. Plate II compares two short exposure photographs taken with Dr. Young's 19-inch reflector, one when the variable was near maximum light, and one near minimum.

At the time that I published a paper on all the variable stars in this cluster in 1935,[3] Chèvremont's observations, though early and visual, were still the best series available on this star, and indicated definitely that the period could not be less than 30 days. The period I found was 33.600 days, and it appeared that the spread obtained in the observations at minimum was due to the difficulty of measuring such a bright object which was overexposed on many plates and had a paucity of comparison stars.

Since then, however, I have acquired many more observations on this star. The 33-day period had been based on scattered observations from 31 nights with the 72-inch telescope at Victoria, and 18 early Mount Wilson plates taken by Shapley. The available observations now, in addition to the published ones just mentioned, are from 68 plates taken with the David Dunlap 74-inch on 65 nights; 25 plates taken on 25 additional nights with the 19-inch telescope; and 289 observations made by the writer on various series of small scale Harvard plates during a visit at the Harvard Observatory. In par-

[1] *Bull. Soc. Astr. France*, vol. 11, p. 485, 1897.
[2] *Les étoiles et les curiosités du ciel*, p. 435, 1882.
[3] *Pub. Dom. Ap. Obs.*, vol. 6, no. 14, 1935.

ticular, the series of plates taken with the 19-inch during the summer of 1948 would appear to demonstrate conclusively that the true period of this star is 67 days.

The same sequence of bright stars has been used as given previously.[3] There would appear to be enough irregularity in the light changes of this type of star so that it is not very satisfactory to attempt to combine scattered observations from many different cycles

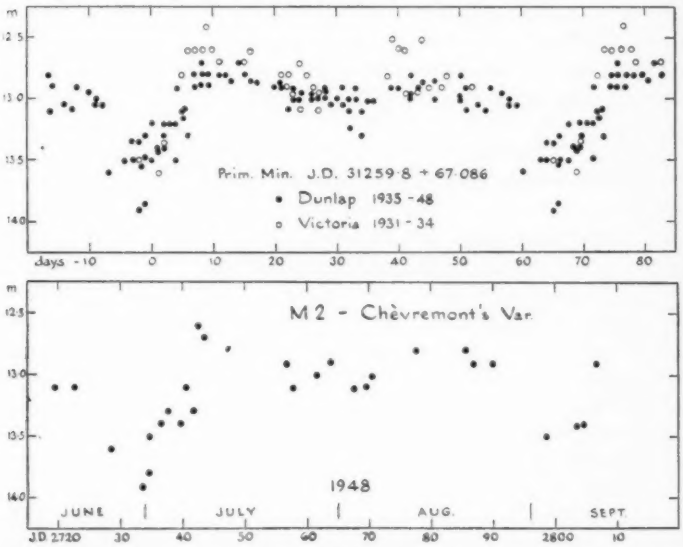

FIG. 1. *Upper*—Observations of Chèvremont's Variable on 121 nights over 18 years are represented with period of 67.086 days. The open circles represent Victoria observations previously published, and indicate some difference in the light changes at that time. *Lower*—A special series of observations in the summer of 1948 at the Dunlap Observatory.

in portraying the light curve. The numerous observations from Harvard plates, scattered over the years from 1928 to 1947, show very clearly the main features, but occasionally observations are at variance with the rest of the curve. This is probably due to two causes: first, that the variable is near the limits of some of the Harvard plates and the errors of observation can be rather large; and second, that

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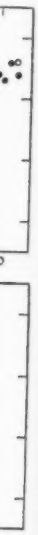

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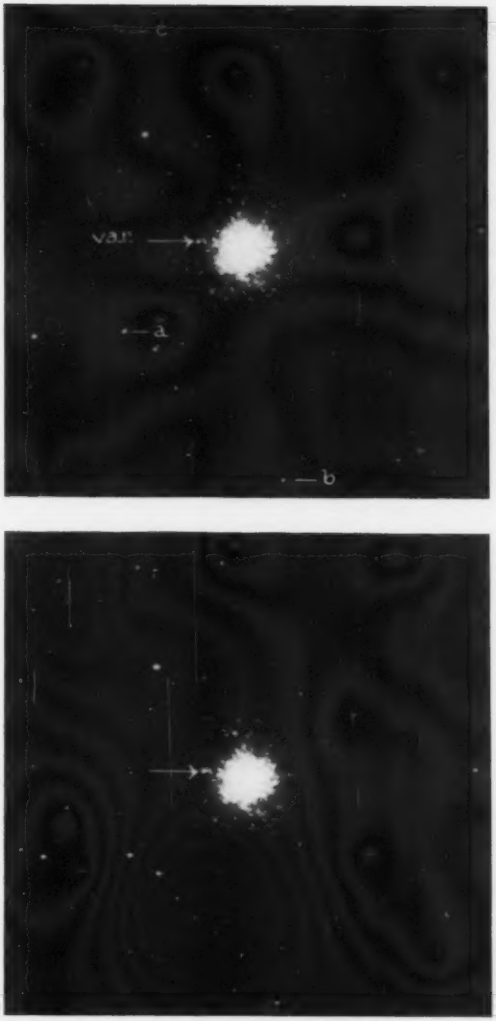

PLATE II

Enlargement of two photographs of Messier 2 taken by J. A. Galt, with the 19-inch David Dunlap reflector, exposure 6^m. Upper, on Sept. 3, 1948, shows Chèvremont's variable near minimum, 13.5; lower, on Sept. 12 shows the variable on rise to maximum, at 12.9. Comparison star photographic magnitudes; a, 12.7; b, 13.0; c, 13.6. Scale, 1 mm. = 12″.1.

the deep and shallow minima for this type of star occasionally interchange and the various features of the light curve are therefore thrown out of phase.

In the light curves pictured in figure 1, only the observations from large scale Canadian plates are plotted, since they are more homogeneous. The upper curve represents observations on 121 nights. The dots are from plates taken at the Dunlap Observatory, principally with the 74-inch reflector. The open circles are the observations made at Victoria, already published. The actual Dunlap observations are not tabulated in this paper since it is intended to publish the magnitudes for several variables in this cluster in a single table at a later date.

The lower curve represents the best existing series of observations now available on this star, taken in the summer of 1948. Of the 29 points represented, 20 are from 19-inch plates. From the Julian Day plot as given, a reader may recover the date and magnitude of the star during this period.

The upper curve has been computed on the basis of the elements:

$$\text{Primary minimum} = \text{J.D. } 2431259.8 + 67.086 \text{ days}$$

which appear to give the best representation of the observations of the last dozen years at least, though a period of 67.129 days is somewhat preferable at times. There is a suggestion that the range varies from time to time, the maxima from the Victoria plates being higher than those observed here, but a colour difference of the instrument and plates used might contribute to this effect. It should however be noted that the double maxima are much more prominent in the Victoria observations than in the later ones taken at this observatory. It can readily be seen why, from these observations, a 33-day period appeared to be indicated. Obviously the later observations demand the longer period. The primary minimum is very deep, but the secondary minimum is so shallow that sometimes it can almost be mistaken for errors of observation of this bright star near maximum.

Professor A. H. Joy has had this star under observation with the spectrograph and will shortly publish his findings on it. His interest in these bright slow variables in clusters has encouraged me to persevere in their problems.

By no means should the photometric investigation of this star be

considered final. A star of this type will certainly bear careful watching over a period of years, preferably in concentrated runs of two to three months.

For some years this star has been considered to be the longest-period Cepheid in a globular cluster, but it must now be taken out of that category. The stars which now hold this position are two variables with similar magnitudes and characteristics, Variables 42 and 84 in Messier 5, with periods of 25 and 26 days, respectively.

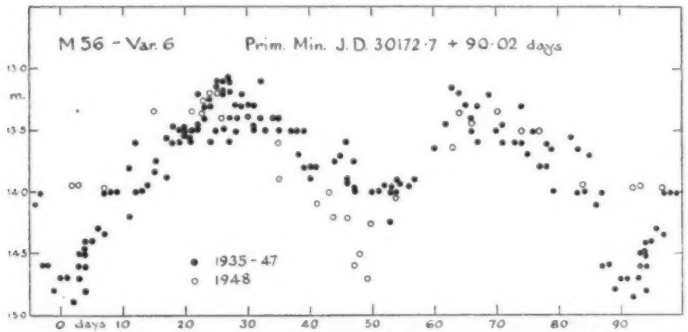

FIG. 2. Observations of Variable No. 6 in M 56 on 174 nights, all at the Dunlap Observatory, represented on the basis of period of 90.02 days, over an interval of 14 years. Open circles indicate observations of 1948, when the variable interchanged its primary and secondary minima.

2. SAWYER'S VARIABLE NO. 6 IN MESSIER 56.

The history of this star is quite recent, since it was discovered by me on plates taken with the Dunlap 74-inch reflector, and announced in 1940,[4] with a plate of the cluster identifying it. Later, in 1941 at the December meetings of the American Astronomical Society,[5] I suggested a 51-day period for the star, from the observations then available. Meanwhile in 1944 Rosino[6] in Italy, who has been working on this cluster since 1941, suggested that an interval of 45.33 days satisfied his observed maxima, though his observations were not well suited to define the light curve at minimum.

[4] *Pub. David Dunlap Obs.*, vol. 1, no. 5, 1940.
[5] *Pub. Am. Ast. Soc.*, vol. 10, no. 5, p. 233, 1942.
[6] *Pub. Oss. Astr. Bologna*, vol. 4, no. 7, 1944.

Like Chèvremont's variable, this is one of the brightest stars within the cluster confines, reaching absolute magnitude −3 at maximum, with a range from 13.1 to 14.9, and its variations are impressive to one studying the cluster. It has a nearby companion star of magnitude 15.7, which is itself attended by two fainter companions. On small scale plates the whole group may tend to blur into the larger image, and introduce an error of measurement. The variable is Küstner[7] No. 284, x −2″.02, y + 37″.06, while its close companion is Küstner No. 285, x −0″.85, y + 40″.70.

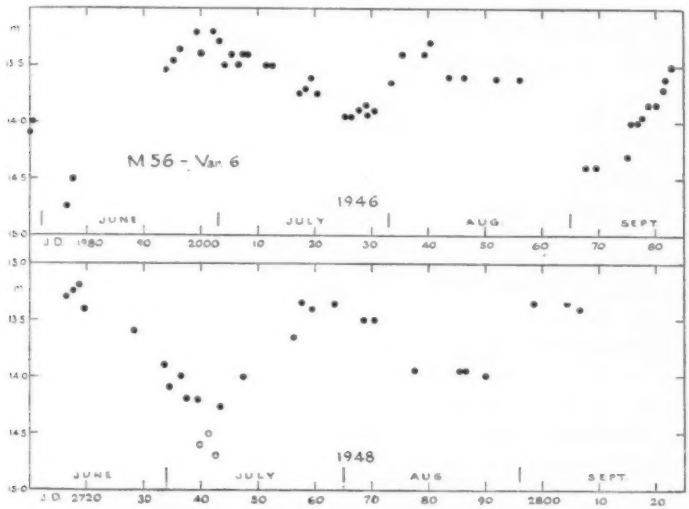

FIG. 3. The two best series available on Variable 6, from plates taken in the summers of 1946 and 1948, chiefly with the 19-inch reflector.

Sequence plates taken here, exposed on Selected Area 64, confirm Rosino's values for the brighter stars of the sequence, and these have been used, except for comparson star *a* which is taken as 12.2.

A total of 226 plates on the cluster has now been taken at the Dunlap Observatory on 174 nights, representing 110 nights with the 74-inch telescope and 64 additional nights with the 19-inch. Also

[7] *Bonn Veröff.*, no. 14, 1920.

observations were obtained at the Steward Observatory on 5 nights. From the accumulated data it now appears that the true period is double the one suggested earlier. Two special series of plates taken in the summers of 1946 and 1948 leave no doubt as to the general characteristics of the light curve, and confirm the fact that shallow and deep minima alternate. The elements for the star were obtained last winter by the writer as follows:

$$\text{Primary minimum} = \text{J.D. } 2430172.7 + 90.02 \text{ days.}$$

The star was followed eagerly through the past summer to see how its behaviour would correspond with prediction. Whereas Chèvremont's variable followed the predicted elements almost precisely, Variable 6 exhibited the RV Tauri surprise of an interchange of primary and secondary minima, as indicated in figure 2. This figure shows all the observations obtained at the Dunlap Observatory from 1935 to date, with the years through 1947 indicated as dots, and the series of 1948 as open circles. Figure 3 portrays the two best series of observations in a Julian Day plot, from which the reader may obtain the magnitude observed on any date. Of the 44 observations obtained in 1946, 35 are from the 19-inch reflector, while of the 29 observations in 1948, 22 are from 19-inch plates. It is hoped soon to publish the Dunlap observations on all the variables in this cluster.

This star also is under spectrographic observation by Professor Joy, and Dr. Rosino has written me that he has acquired 160 plates on this cluster in the years 1946 to 1948, from which he hopes to derive additional material on the variables.

I wish to express my indebtedness to the following for the large amount of observational assistance in this program: to Dr. F. S. Hogg and Mr. Gerald Longworth for help with the 74-inch, and to R. W. Tanner, D. K. Norris, and J. A. Galt for assistance particularly in taking the 19-inch plates; and to Dr. Harlow Shapley for permission to use the Harvard plate collection.

Richmond Hill, Ontario,
January, 1949.

OUT OF OLD BOOKS

By Helen Sawyer Hogg

The Early Discovery of Four Globular Clusters

MUCH has been written about the importance and the thrill of the discovery of a new planet. Even the non-astronomical public tries to imagine the feelings of "some watcher of the skies when a new planet swims into his ken." Too little, however, is written about the early discoveries of those vast aggregations of suns, the globular clusters. A new planet may seem to us here on earth to be a momentous discovery, but in the cosmic scheme of things it is less important than a gigantic stellar system composed of thousands upon thousands of stars—where the possible number of planets is quite unknown.

The actual accounts of the discoveries of globular clusters are to be found in scarce volumes. Up until the time of William Herschel most of the discoveries had been made in continental Europe, so that most of the discovery announcements are not in English.

Until two centuries ago, to the best of my knowledge, seven globular clusters had been discovered. In order of discovery, by our accepted nomenclature, these are: Messier 22 in Sagittarius, Omega Centauri, Messier 5 in Serpens, Messier 13 in Hercules, Messier 4 in Scorpio, Messier 15 in Pegasus, and Messier 2 in Aquarius. Halley's account of the discovery of Messier 13, the great globular cluster in Hercules, together with his description of the two clusters found earlier, has already been reprinted in this Journal, February 1947. In this issue we reprint the discovery announcements of the other four globular clusters known before 1750.

Messier 5 was discovered on May 5, 1702 by the German astronomer Gottfried Kirch, 1639-1710. He is also noted as the discoverer of the comet of 1680, and the famous variable Chi Cygni. In 1705 he was appointed Director of the Royal Observatory in

Berlin. Not the least interesting fact about Kirch is that his wife Margarethe assisted him in observing, recording and computing. She herself discovered a comet in 1702.

Actually the discovery of the globular cluster Messier 5 made by Gottfried Kirch is given to us in the words of his wife Margarethe. The account is published by J. L. E. Dreyer in A Supplement to Sir John Herschel's "General Catalogue of Nebulae and Clusters of Stars", *Transactions of the Royal Irish Academy*, vol. 26, p. 397, 1878, as a note to the catalogue.

> M. 5. Discovered by Gotfried Kirch on the 5th May, 1702. The following is an extract from Marie Margarethe Kirch's diary, now in the possession of Lord Lindsay:—"Durch solches Suchen [for the comet then visible] fand mein Mann durch eben diesen 3 Sch. Tub. hoch über μ [Serpentis, mentioned in the foregoing] ein neblicht, aber doch deutliches Sternchen, es hatte viel feine andere Sternchen um sich, doch eins stand sonderlich per Tubum über diesen ungefähr also [then follows a rough sketch of a star and the "nebulous star" below it] . . . May 6. Das neblichte Sternchen haben wir deutlich auf seiner vorigen Stelle gefunden." At 10.30, P.M., on the date mentioned, 5 M would be about 8° above μ Serpentis, and the sketch made by M. M. Kirch represents exactly the relative position of 5 M and the star 5 Serpentis, as seen in an inverting telescope (per tubum). Communicated by Dr. R. Copeland.

We learn from this account that Gottfried Kirch, while looking for a comet in 1702, found this nebulous star on May 5, and that the next night, May 6, he and his wife together confirmed the discovery of the object. It was Margarethe Kirch who drew the chart of its position and made up the record. Almost fifty years later the object became known as Messier 5 when Messier published his first list of nebulae and star clusters in 1771.

A decade after the discovery of Messier 5, Halley found the globular cluster in Hercules. Thirty years elapsed before the next globular cluster was found. Probably the next one to be sighted was Messier 4, which was found by de Chéseaux in about 1745. The exact year is unknown. M. de Chéseaux is best known for the comet of 1744 which bears his name. This comet was actually discovered by Klinkenberg at Haarlem on December 9, 1743, but it was de Chéseaux who called attention to its six tails. At about this time he compiled a list of 21 nebulous objects which he sent to his grandfather, M. de Réaumur, then president of the French

Academy. There is reference to this work by Maraldi and Legentil in the Mémoires of the Academy in 1746, but the actual letter and list remained filed away and unpublished until 1891, when Bigourdan reprinted it in the *Paris Annales*, Observations, 1884. In his letter, de Chéseaux states that most of the nebulae in Derham's list do not truly merit the name, but that he himself has drawn up a list of 21 true nebulae and star clusters. The criticism de Chéseaux made of Derham's list is absolutely correct (cf. this Journal, July-August, 1947, p. 235). His own list is the best and most complete catalogue of nebulous objects and stellar groups to be compiled up until that time, and has received too little recognition. Number 19 on this list is the globular cluster Messier 4, which de Chéseaux describes as follows:

19. Une qui est près d'Antarès, dont j'ai trouvé, pour cette année, l'A.D. de 242° 1′ 45″ et sa déclinaison 25° 23′ 30″. Elle est blanche, ronde, et plus petite que les precedentes [Omega Centauri and Messier 22]; je ne sache pas qu'on l'ait jamais remarquée.

Apparently de Chéseaux suspected that he had discovered a hitherto unknown object here, but the literature then was so scattered that he could not be sure.

The discovery of the next two clusters, Messier 15 and 2, was made by Giovanni Maraldi in 1746 probably just a bit later than de Chéseaux's discovery of Messier 4. Maraldi, a relative of the famous Cassini family, assisted at the Paris Observatory and edited the Connaissance des Temps. He found his two famous globular clusters while observing a comet in September 1746. This comet, which passed perihelion early in 1747, was discovered by de Chéseaux on August 13, 1746, and last observed by Maraldi on December 5 of that year. In the *Mémoires* of the *Académie des Sciences*, 1746, page 58, Maraldi describes his discovery in his paper entitled, Observations de la comète qui a paru au mois d'août 1746.

Le 7 Septembre j'aperçus entre l'étoile ϵ du Pegase et β du Petit-cheval, une étoile nébuleuse assez claire, qui est composée de plusieurs étoiles, dont j'ai déterminé l'ascension droite de 319^d 27′ 6″, et la déclinaison septentrionale de 11^d 2′ 22″.

Le 11 Septembre j'en observai une autre dont l'ascension droite est de 320^d 7′ 19″, et la déclinaison de 1^d 55′ 38″ vers le midi, à peu près dans le même parallèle ou devoit être la Comète. Celle-ci est ronde, bien terminée, et plus

claire au milieu; elle occupe environ 4 ou 5 minutes de degré, et n'est environnée d'aucune étoile, même à une assez grande distance: on n'envoyait aucune dans toute l'ouverture de la lunette, ce qui me parut fort singulier; car la plûpart des étoiles qu'on appelle *nébuleuses* sont environnées d'un grand nombre d'étoiles, ce qui a fait juger que la blancheur que l'on y découvre, est l'effect de la lumière d'un amas d'étoiles trop petites pour être aperçues par les plus grandes lunettes. Je pris d'abord cette nébuleuse pour la Comète, je crus qu'enfin le temps étoit devenu favorable et le ciel assez serein pour nous permettre de voir distinctement l'atmosphère de la Comète avec son noyau.

La difficulté de voir la Comète à la vûe simple dans le temps même le plus serein, qui m'a donné occasion de voir ces nébuleuses, me fit sentir aussi la nécessité d'ébaucher la théorie de la Comète dès le commencement que nous l'aperçumes, afin de la retrouver en cas que nous fussions quelque temps sans la voir, comme il pouvoit arriver par le mauvais temps, ou par la clarté de la Lune.

Maraldi's description of Messier 15 in Pegasus is very brief, but he was apparently greatly impressed, as have been many sky watchers since his time, with the striking appearance of the spectacular cluster Messier 2 set in a field almost devoid of other stars, when viewed in a telescope. This appearance of globular clusters, a rich cluster against an almost starless background, was noted by William Herschel half a century later, and led to his frequent use of the term "insulation" as applied to globular clusters, which seemed to him, quite rightly, set apart from the few scattered stars surrounding them.

Although Maraldi was interested in his new object, in his account we detect a certain amount of disappointment, that what he at first took for a particularly fine view of the comet, in which he was seeing its atmosphere distinctly, proved merely to be a nebula.

It is well known that Messier made his catalogue of nebulous objects as a result of his cometary studies, but we see from the references here quoted that decades before his time, the pursuit of comets was responsible for the discovery of important "nebulous stars."

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